Submesoscale Routes to Lateral Mixing in the Ocean

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LONG-TERM GOALS

To determine whether lateral mixing at O(1-10 km) scales is due to a balanced or unbalanced downscale cascade from the mesoscale, or due to local vertical mixing by internal waves and surface forcing.

OBJECTIVES

Our work is testing hypothesis 3 of the white paper "Scalable Lateral Mixing and Coherent Turbulence": Non-QG, submesoscale instabilities feed a forward cascade of energy, scalar and Ertel PV variance, which enhances both isopycnal and diapycnal mixing. Related hypotheses are that submesoscale variability is associated with coherent structures and anisotropic mixing. Further, submesoscale processes are inherently vertical, as well as horizontal, and that submesoscale processes facilitate cross-front exchange.

APPROACH

Our approach is to run a number of process studies using a three-dimensional non-hydrostatic model written by Amala Mahadevan (PI from Boston University *e.g.* Mahadevan and Tandon 2006). The typical model resolution for resolving submesoscales is about 1 km in the horizontal. We examined processes in a domain approximately 100 km x 200 km, but recently, we have improved the model to run on much larger domains (approximately 500 km x 1000 km) at the same horizontal resolution.

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WORK COMPLETED

Our collaboration with Takeyoshi Nagai (TUMST, Japan) and Eric Kunze (also LATMIX PI) has contributed to this work.

The work reported last year had analyzed the spreading of tracer on isopycnal surfaces beneath a mixed layer front. Model simulations of a baroclinically unstable mixed layer front (Mahadevan et al., 2010) were performed in a zonal channel with a north-south density gradient confined only to the mixed layer. Tracer streaks were laid out on isopycnal surfaces (initially flat) beneath the mixed layer. Our analysis shows the prevelence of three regimes in tracer disperson: an early diffusive regime, a regime of exponential growth in tracer dispersion, and finally, a Richardson-like regime. This work has been accepted for publication in the Journal of Physical Oceanography and is in press.

In year 3, we have used a trans-Kuroshio observational section from summer 2008 to initialize our sub-mesoscale resolving oceanic model, PSOM. This is leading to some very exciting results about the forward cascade of energy and has important energy dissiptaion implications vis-à-vis the sink of energy associated with geostrophic currents, as shown in the Results section.

Another part of this project consists of improvement in sub-grid fluxes of our submesoscale model. Graduate student Sonaljit Mukherjee in guidance with PI Tandon has coupled GOTM (the Generalized Ocean Turbulence Model) to PSOM, to provide the option of a large number of sub-grid mixing parameterizations. Another student X.Yao has done simulations with the 2010 test cruise profiles presented at the last LATMIX PI meeting (She plans to continue with Miles Sundermeyer for her PhD in Fall 2011). In the next year we plan to analyze dissipation and other diagnostics in the model runs that are relevant to the 2012 experiment wit the coupled GOTM-PSOM model. Funded through an NSF project, postdoc Dr. Sanjiv Ramachandran has implemented the Smagorinsky parametereization in an inhomogeneous non-isotropic sub-mesoscale resolving grid. This is a new technique, since LES parameterzations are typically isotropic. Our initial results are encouraging.

RESULTS

In preparation for the 2012 fieldwork in areas of more intense density gradients, we initialized the model with a section from the 2008 Kuroshio front observations (Nagai *et al.* 2009). This leads to intense mesoscale and sub-mesoscale structures. An exciting result is the spontaneous generation of near-inertial internal waves from the meso- and sub-mesoscale instabilities of the front, without any surface forcing. (Figures 1and 2)

Moorings placed in the numerical model show that the intrinsic frequency of the near-inertial waves gets smeared by the Doppler effect due to the mean current. Therefore a number of Lagrangian floats are released into the model, showing that the intrinsic frequency of the near-inertial waves is between f and 2f. These near-inertial waves have large divergence and convergence patterns near the front, and even after substantial spatial and temporal averaging, they have large fluxes, comparable to the wind-generated fluxes.

The source of near inertial shear is conventionally considered to be wind forcing, so these new results are quite striking in that the instabilities and loss of balance leads to spontaneous generation of near-inertial waves that lead to local energy dissipation and mixing in in the vicinity of the front.

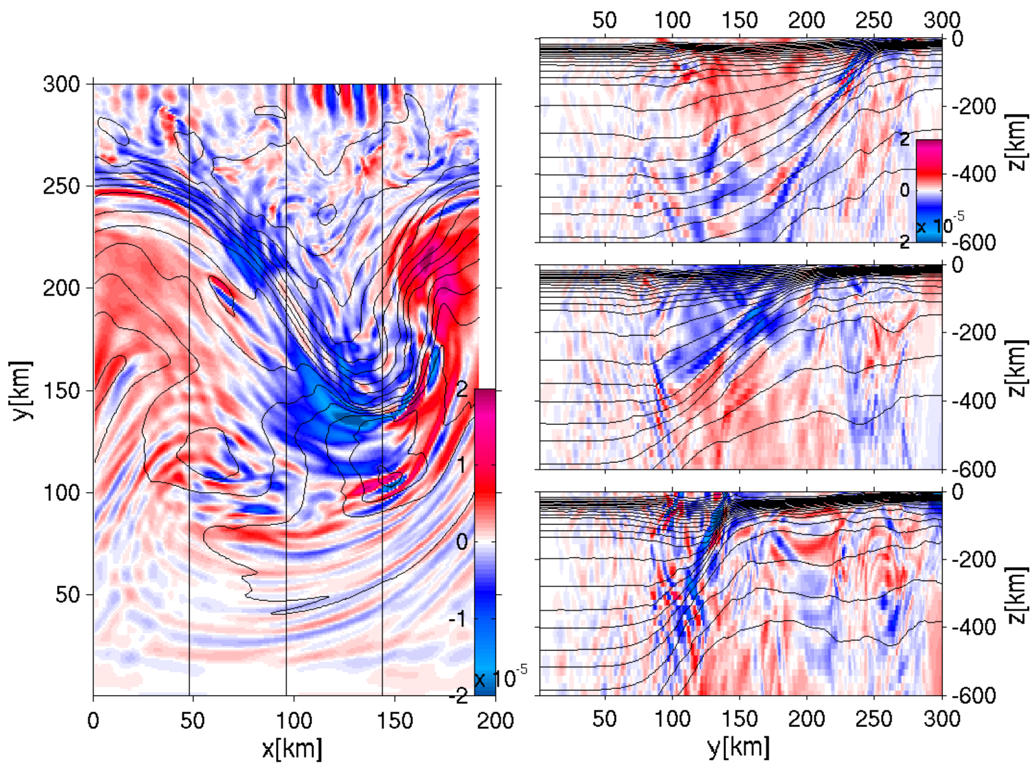

Figure 1 This figure shows the horizontal divergence field in the intense frontal simulation, initialized by a hydrographic section from 2008 observations assumed in thermal wind balance. The left panel is at 100m depth, and the alternating bands of divergence are signatures of near inertial waves. The right hand panel shows the sections at 48, 96 and 144 km. This situation is similar to generation of internal waves at atmospheric front (Plougonven and Snyder, GRL 2005).

Our results for the anisotropic Smagorinsky model (Roman et al., 2010) are for simulations of a frontal system both with and without downfront winds. The domain is large enough in size and fine enough in resolution to resolve both mesoscale and submesoscale features. Results from the new subgrid model are consistent with those observed in previous studies with the PSOM model using constant lateral subgrid viscosities. Fig 3 and 4 show a case where the baroclinicity is confined to the mixed layer. Fig 3. shows the evolution of near-surface density and the horizontal subgrid viscosity (K_h), where the frontal regions exhibit the highest values of K_h. Fig 4 shows the potential vorticity field alongside the horizontal and vertical subgrid dissipation of kinetic energy (epsilon). Regions with negative potential vorticity are typically associated with high values of epsilon, signaling forward cascade of energy. The subgrid dissipation, epsilon, is determined primarily by vertical shear with horizontal gradients contributing negligibly to it. The subgrid dissipation of the density variance, Chi, is also primarily due to vertical gradients although the lateral density gradients contribute non-negligibly to Chi, especially near the front. The subgrid dissipation, epsilon, is in the similar range of values to Eric Skyllingstad's recent LES results.

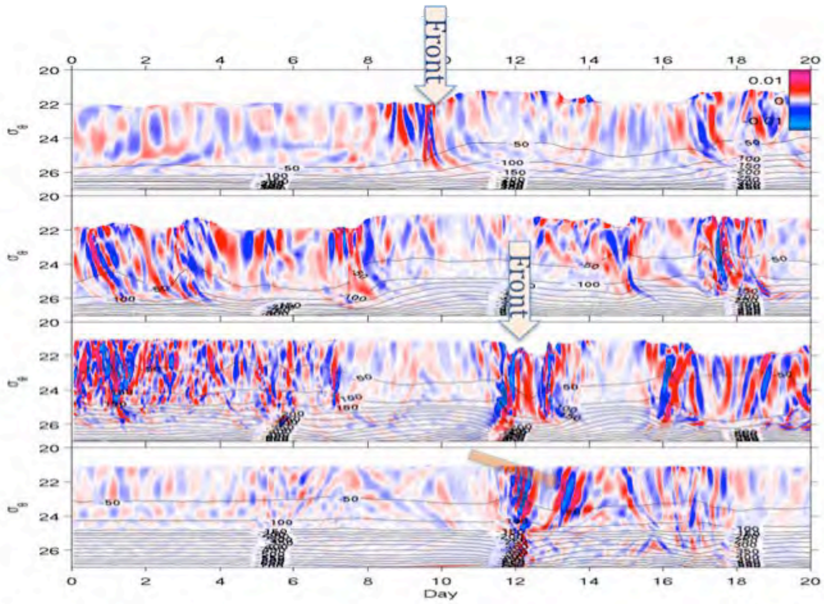

Figure 2 Hovmuller diagram showing the upward and downward propagation of phase in desity space for the near-inertial waves generated in Figure 1.

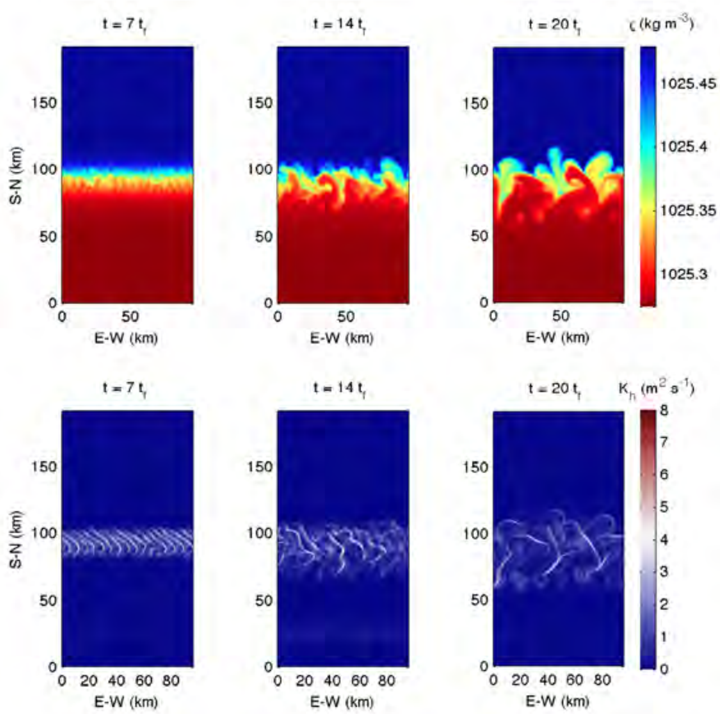

Figure 3: Density at the surface and horizontal mixing coefficients (Smagorinsky) for the LES framework adapted into a sub-mesoscale ocean model.

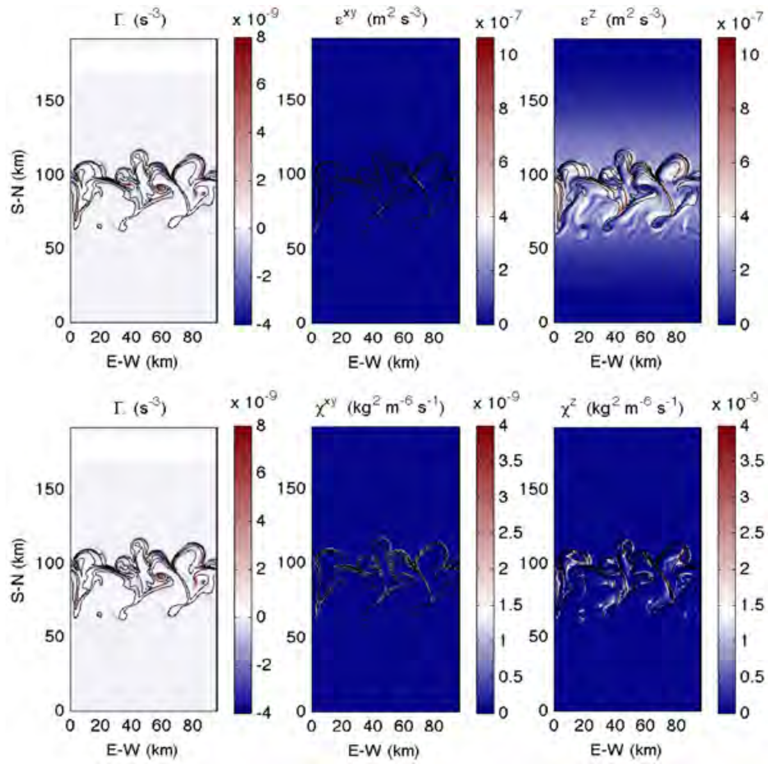

Figure 4: Potential Vorticity, Dissipation (horizontal and vertical contributions for a frontal simulation forced with downfront winds using the non-isotropic Smagorinsky parameterization.

OTHER ACTIVITIES

Mahadevan, Tandon and Badin participated in the workshop titled Balance, boundaries and mixing in the climate problem, organized by the Centre de recherches mathématiques, Montreal.

Mahadevan, and Badin individually made presentations at the GFD summer school at Woods Hole in summer 2011.

Other seminars and presentations include colloquia at URI, SMAST/UMass, and University of Sao-Paulo, Brazil (Tandon), Woods Hole, Princeton, Hamburg (Badin).

Tandon's research group presented ocean circulation related experiments at the Working Waterfront Festival in New Bedford Harbor in September 2010 and September 2011. They also presented experiments at the "Making waves" event by the New Bedford Ocean Explorium. Mahadevan and Badin presented experiments at the Boston Museum of Science.

REFERENCES

Nagai, T., A. Tandon, H. Yamazaki, and M. J. Doubell, 2009, Evidence of enhanced turbulent dissipation in the frontogenetic Kuroshio Front thermocline, *Geophys. Res. Lett.*, 36, L12609, doi:10.1029/2009GL038832.

Plougonven, R. and C. Snyder, 2007, Inertia-gravity waves spontaneously generated by jets and fronts. Part I: Different baroclinic life cycles. J. Atmos. Sci., 64, 2502-2520.

PUBLICATIONS

Mahadevan, A., A. Tandon and R. Ferrari, 2010, Rapid changes in mixed layer stratification driven by submesoscale instabilities and winds, *J. Geophys. Res.*, 115, C03017, doi:10.1029/2008JC005203.

Badin, G., A. Tandon and A. Mahadevan, Lateral mixing in the pycnocline by baroclinic mixed layer eddies, Journal of Physical Oceanography, In Press, 2011.

Manuscripts in Preparation

Direct Observations of Microscale Turbulence, Subduction and Upwelling in the Kuroshio Front, by Takeyoshi Nagai, Amit Tandon, Hidekatsu Yamazaki, Mark J. Doubell, Scott Gallager, *In review*, Journal of Geophysical Research-Oceans, 2011.

Idealized mixed-layer simulations using multiple turbulence parameterizations, S. Mukherjee, A. Tandon, S. Ramachandran and A. Mahadevan.

M.S. Thesis

Yao, X., M.S. Thesis, Shallow Mixed Layer Process Simulations Inspired by 2010 LATMIX Oceanographic Test Cruise Dataset.